Spatial heterogeneity and clouds

(to inspire discussions)

Breakout Session 4 - Impact of spatial heterogeneity and subgrid variability on aerosol and cloud processes

ASR/ARM joint PI meeting 2023

Zhibo Zhang

(Physics Dept./UMBC)

Biased heavily toward my own research--warm cloud, precipitation, ENA and radiation

Discussion questions

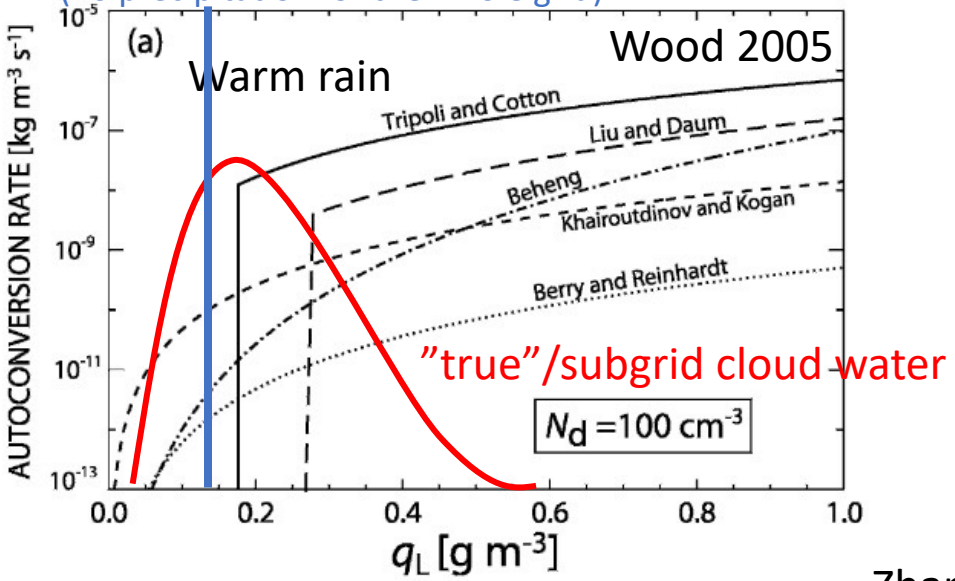
- For which quantities do we need to consider “heterogeneity” (drivers and impacted quantities)?
- At what length scales does the heterogeneity have significant impacts?
- What observational design modifications to typical ARM deployments would enable better study of spatial heterogeneity and subgrid scale variability?
- How can we use the range of ARM platforms - ground-based, TBS, UAS, AAF - together to more effectively characterize spatial heterogeneity and subgrid scale variability?
- With current available ARM data or current/ongoing field campaign designs, what heterogeneity related problems can we tackle and what can we not?
- For the effects of heterogeneity, what can be solved by high resolution modeling (as computational power increases) and what can not be solved?
- For those problems that can be solved by increasing resolution, is our model ready for it? For those cannot be solved, which directions should we pursue?

For which quantities do we need to consider "heterogeneity"?

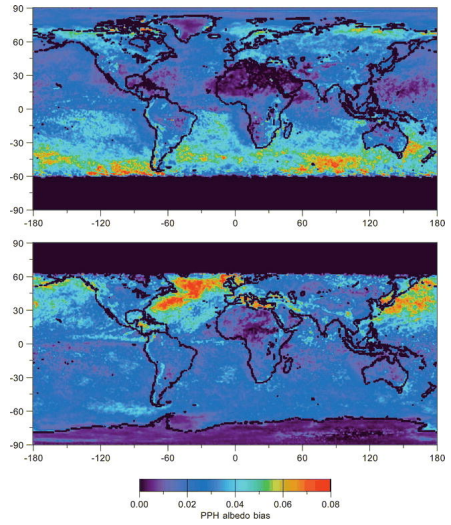
- Cloud properties
  - Cloud water & optical depth
  - Cloud droplet number concentration
  - Cloud phase (ice vs. water) partition
  - Cloud vertical structure and overlapping with lower atmosphere and surface
  - … …

Grid mean cloud water
(no precipitation for the whole grid)

For example:



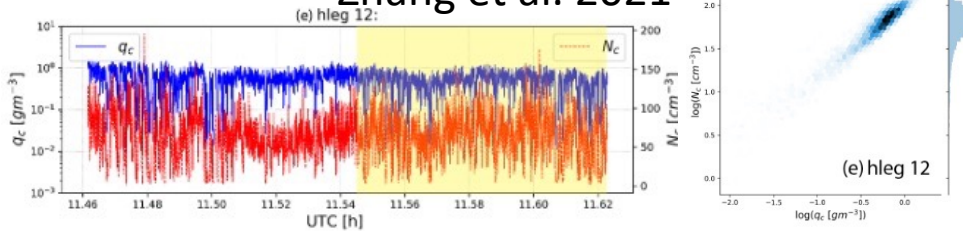
Radiation

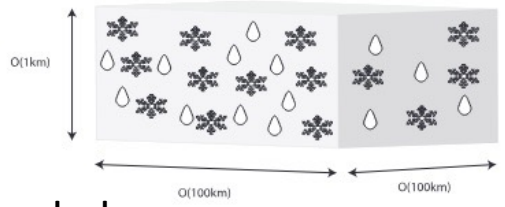


Oreopoulos et al. 2007

CDNC (co)variation

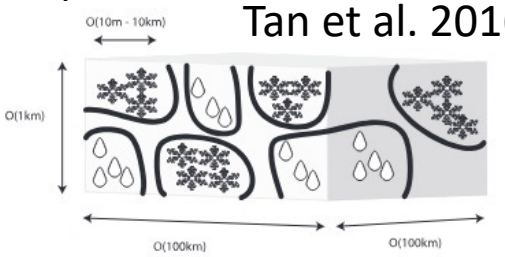
Zhang et al. 2021

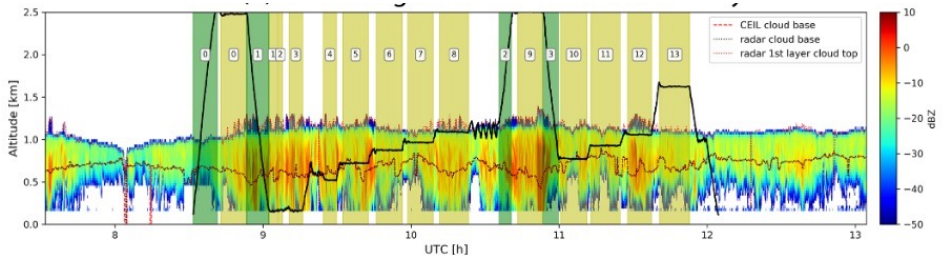




Cloud phase

Tan et al. 2016

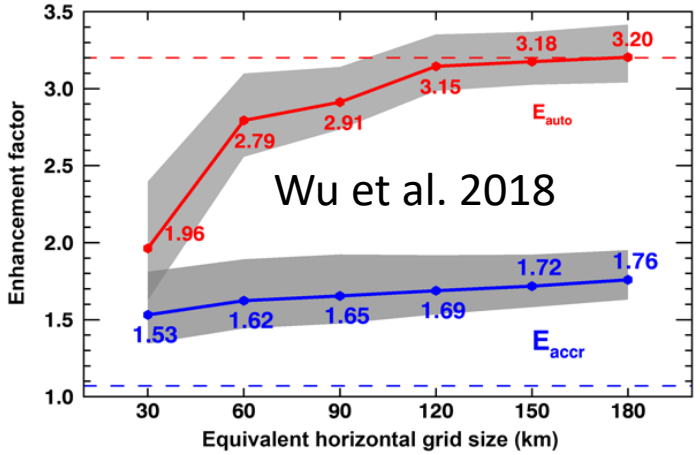


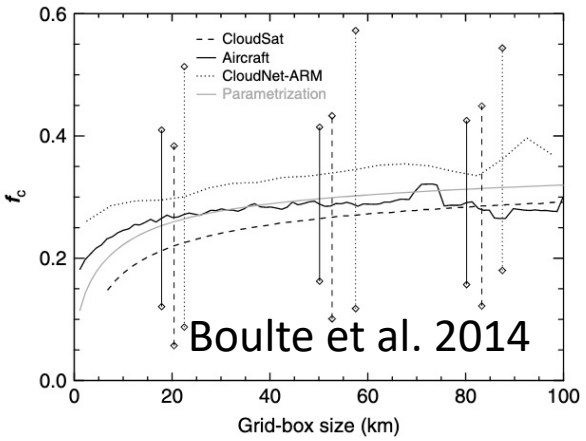


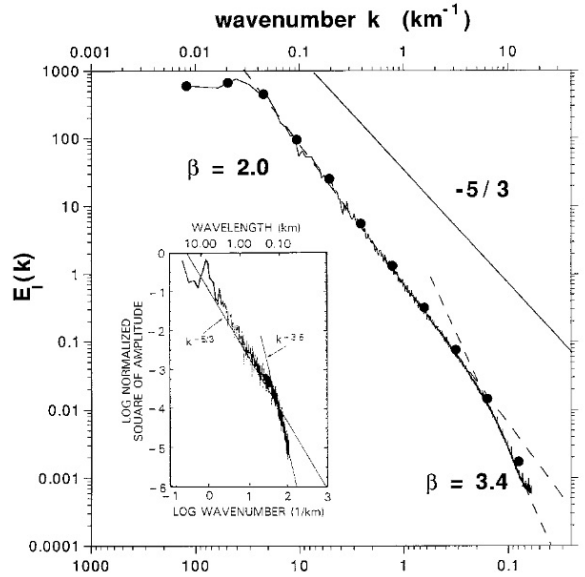
Cloud-land coupling

At what length scales does the heterogeneity have significant impacts?

- Heterogeneity of cloud properties is generally “scale-dependent”.
  - Heterogeneity usually increases with increasing scales, but often becomes asymptotic above certain scale (if cloud type/regime remains the same).
- Different physical processes have different “operating” spatial (and temporal) scales



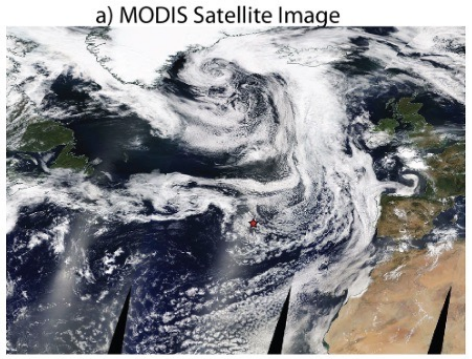


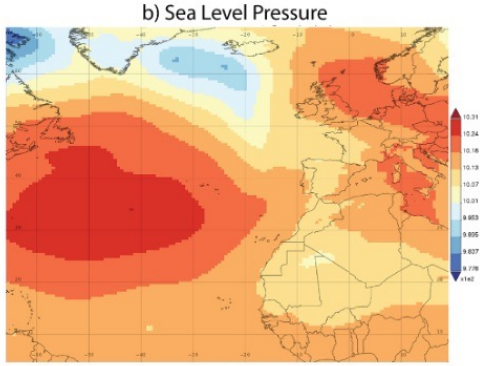


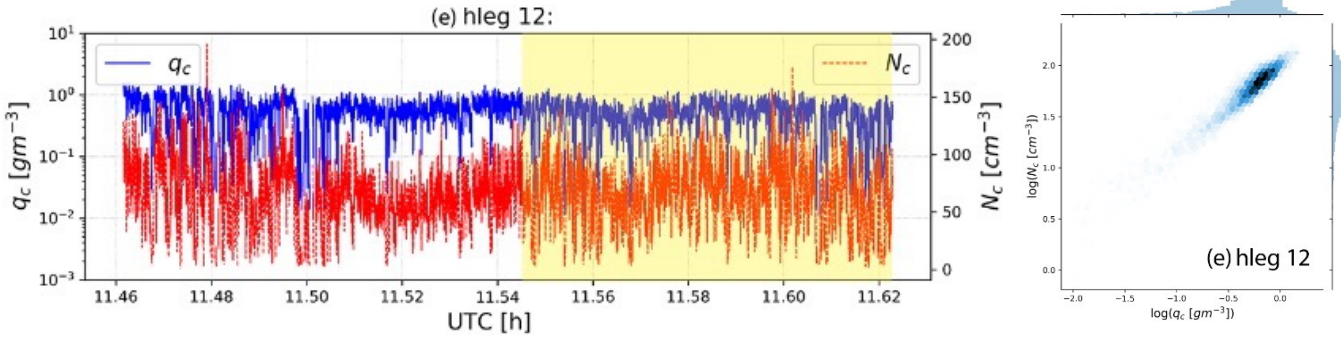
Davis et al. 1996

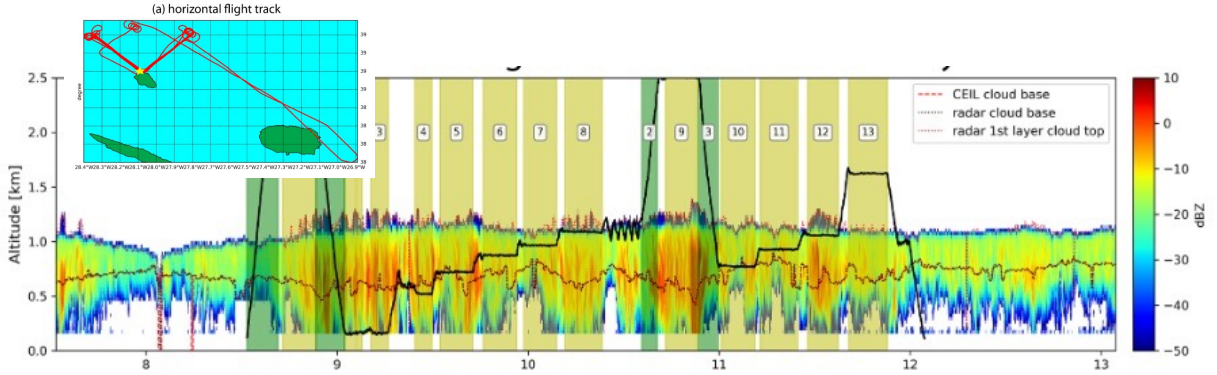
“**scale-aware**” parameterization may become increasingly important as GCM resolution increases from ~100km to ~10km.

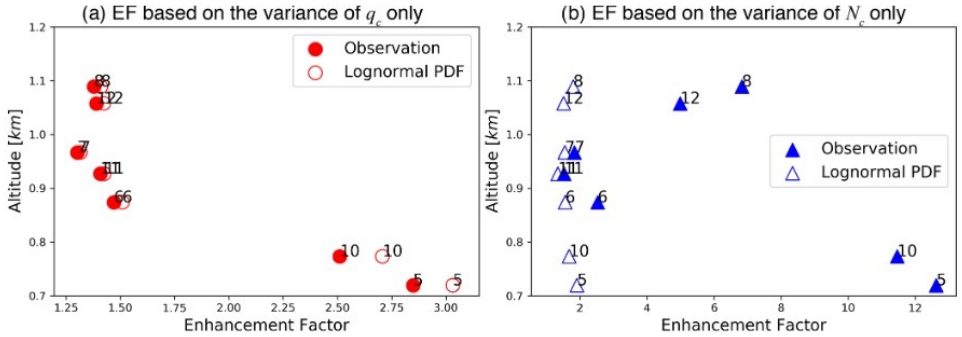
How can we use the range of ARM platforms - ground-based, TBS, UAS, AAF - together to more effectively characterize spatial heterogeneity and subgrid scale variability?

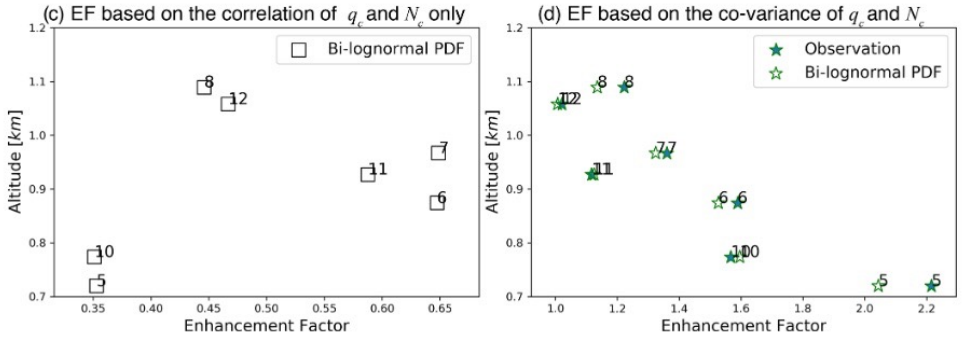












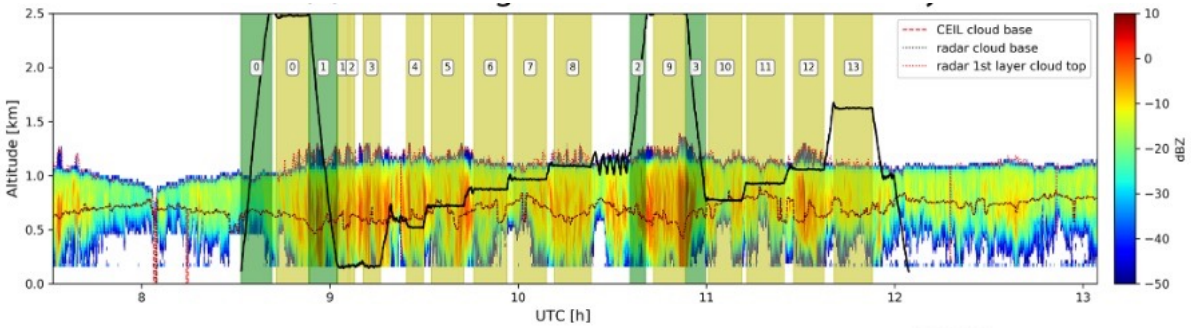
$$E = \frac{\int_{N_{c,\min}}^{\infty}\int_{q_{c,\min}}^{\infty} q_c^{\beta_q} N_c^{\beta_N} P(q_c, N_c)\,\mathrm{d}q_c\mathrm{d}N_c}{\langle q_c\rangle^{\beta_q}\langle N_c\rangle^{\beta_N}},$$

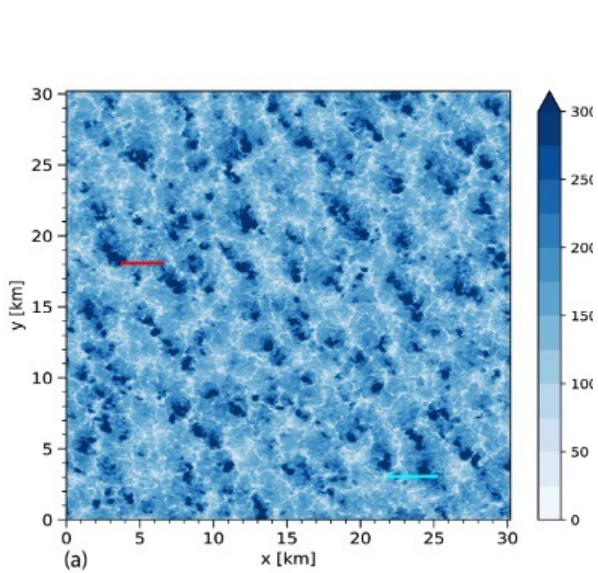
$$E = E_q\left(\nu_{q_c}, \beta_q\right)\cdot E_N\left(\nu_{N_c}, \beta_N\right) \cdot E_{\mathrm{COV}}\left(\rho_L, \beta_q, \beta_N \nu_{q_c}, \nu_{N_c}\right),$$

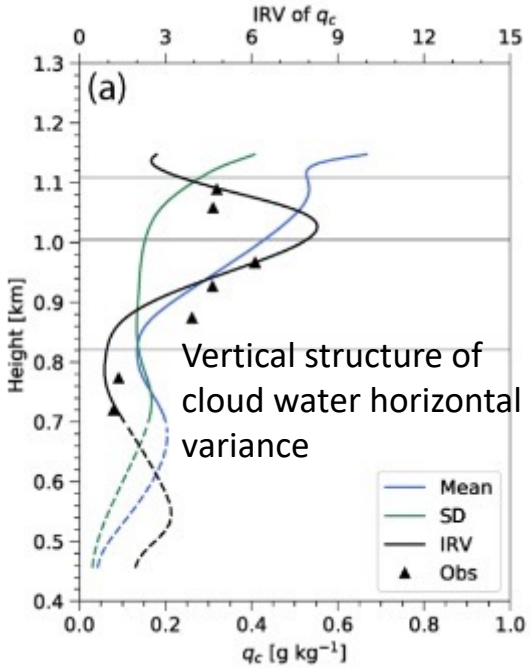
$$P(q_c, N_c) = \frac{1}{2\pi q_c N_c \sigma_{q_c}\sigma_{N_c}\sqrt{1-\rho_L^2}}\exp\left(-\frac{\zeta}{2}\right)$$

For the effects of heterogeneity, what can be solved by high resolution modeling (as computational power increases) and what can not be solved?

In situ and ground observations (slice or cross-section)





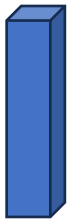


Vertical structure of cloud water horizontal variance

Covert et al. 2022

- High-resolution model (LES, LASSO, MMF…) output can be used to simulate the full 3-D structure (in comparisons to slice/cross-section observations)—very useful for evaluating and improving ESM parameterization, e.g., turbulence, precipitation...
- The 3-D interactions between clouds/surface and radiations are still not solved even by high-resolution models.

ESM grid
(inter-column RT is negligible)



High-resolution model column
(inter-column RT is significant/potentially important)

A few (random) thoughts

- Different parameterization schemes often use different/inconsistent treatments/assumptions about cloud heterogeneity
  - For example, turbulence (CLUBB), microphysics (MG), and radiation (COSP) are often based on different cloud heterogeneity models.
- Temporal heterogeneity (sub-time-step) should not be forgotten/ignored (see my poster #101 Wed. morning).

Discussion questions

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